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Thermal Stability of a Laser-Clad NiCrBSi Coating Hardened by Frictional Finishing

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Abstract. Frictional treatment decreases surface roughness of a NiCrBSi laser coating and increases its microhardness and abrasive wear resistance. Even after softening annealing at 900 °C, the coating subjected to frictional treatment preserves its advantage in hardness and wear resistance over the original clad coating. Annealing at 1000 °C after frictional treatment ensures less effective growth of the hardness and wear resistance of the coating as compared to annealing of the undeformed coating due to the limited precipitation of large $Cr_{23}C_6$ carbides on the deformed surface, which form a wear-resistant framework.

INTRODUCTION

NiCrBSi coatings produced by laser cladding are used for surface hardening and restoration of worn machine part surfaces [1-5]. However, layers formed by gas powder laser cladding are characterized by significant surface roughness, this being currently eliminated, as a rule, by disk grinding. The authors of [6] demonstrated the applicability of frictional treatment by sliding indenters as a method of intensive plastic surface deformation for the finishing of NiCrBSi laser coatings. This processing can find a wide industrial application in the production of machine parts at metal-working centers [7].

A considerable thermal softening of a NiCrBSi coating at temperature ranging between 900 and 950 °C was reported in [8], where a new phenomenon of an increase in the hardness and wear resistance of a laser coating due to high-temperature (1000 °C and higher) annealing forming a wear-resistant framework from large particles of strengthening phases (carbides, borides) was also demonstrated. The above-mentioned large particles precipitate under cooling (from the annealing temperature) from metastable oversaturated solid solutions formed when metal is rapidly cooled in the course of laser cladding. The discovered phenomenon is used to develop a combined method including laser cladding and stabilizing annealing [9]. The method provides producing Ni-based coatings with an especially high level of heat resistance [8].

The aim of this paper is to study the effect of thermal action (at temperatures from 900 to 1000 °C) on the hardness and abrasive wear resistance of a NiCrBSi laser-clad coating additionally strengthened by frictional treatment and to determine therefrom i) the thermal stability of the surface-deformed coating and ii) the efficiency of combined deformational-heat treatment (frictional treatment + high-temperature annealing) in order to improve the mechanical properties of the coating.

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MATERIAL AND EXPERIMENTAL PROCEDURE

PG-SR2 powder (0.48% C, 14.8% Cr, 2.6% Fe, 2.9% Si, 2.1% B and the rest Ni) was used as a coating material. Low-carbon (0.20% C) steel plate was coated by cladding in two passes of continuous CO_2 laser with a radiation power of 1.4 to 1.6 kW, a velocity of 160 mm/min, a powder consumption of 2.9 to 3.8 g/min, the size of the laser spot on the surface being 6×1.5 mm.

Frictional treatment of clad flat specimens with an electropolished surface was made by a hemispheric indenter made of fine-crystalline dense boron nitride indenter under a load of 350N in air, with five-time scanning at an average velocity of 0.013 m/s, a stroke length of 18 mm, indenter displacement of 0.1 mm for a double stroke.

Thermal action (annealing) was applied by heating the specimens to 900 and 1000 °C, with 1-hour holding and furnace cooling.

The coating surface was examined with the use of a Vega II XMU scanning electron microscope and a Wyko NT-1100 optical profilometer. Microhardness was measured by a Wilson & Wolpert 402 MVD microhardness meter under a load of 0.245 N on the Vickers indenter. The measurement error was determined with a confidence level p=0.95.

Abrasive wear testing was performed by reciprocating sliding of the coated specimens against a fixed silicon abrasive (SiO_2, ~1000 HV), with a load of 49 N, average sliding velocity V=0.175 m/s and friction length l=9 m. Specimen mass loss Δm and wear intensity I_h were determined, the latter being calculated by the formula $I_h=\Delta m/(\rho SL)$, where Δm is specimen mass loss, g; ρ is specimen material density, g/cm^3; S is the geometric contact area, cm^2; L is the friction length, cm.

EXPERIMENTAL RESULTS AND DISCUSSION

According to Fig. 1a, the initial electropolished surface of the NiCrBSi coating is characterized by the mean arithmetic deviation of the roughness profile Ra=250 nm. Frictional treatment forms a higher-quality surface, smoothed, with much lower roughness (Ra=60 nm), Fig. 1b, 2a. The examination of the coating structure on the transverse section demonstrated that, as a result of friction processing, a highly dispersed 5-7 µm thick layer is formed on the laser-clad coating surface (Fig. 1c). In this surface layer there occurs a complete strain-induced dissolution of Ni_3B particles, as well as dispersion and partial dissolution of $Cr_{23}C_6$ carbides in the γ-Ni solid solution, see Fig. 1c. The friction processing, as compared to the initial electropolished macrocrystalline state, offers high levels of microhardness (850 and 570 HV 0.025 respectively) and low levels of abrasive wear intensity in testing against a fixed silicon abrasive (I_h=0.85×10^{-6} after frictional treatment and I_h=1.05×10^{-6} after electropolishing), Tables 1 and 2.

As a result of one-hour annealing at 900 °C, both after electropolishing and after friction processing, the coating becomes softened (respectively, to 530 and 640 HV 0.025), Table 1. Herewith, abrasive wear intensity increases to 1.20×10^{-6} for the undeformed coating and to 0.95×10^{-6} for the deformation-hardened one (Table 2). Thus, after heating to 900 °C, the coating hardened by frictional treatment retains its advantage in hardness and wear resistance not only over the most softened (at 900 °C) undeformed coating, but also over the initial laser-clad coating (without deformation processing followed by heating).

Figure 3a presents a portion of the laser coating in the initial electropolished state after abrasive wearing against silicon. Besides smoothed area, it is characterized by the presence of furrows and grooves with sharp edges, which are characteristic of wear by the mechanism of microcutting. After frictional treatment and softening annealing at 900 °C, the share of elongate smoothed areas of plastic strain (Fig. 3b), characteristic of the mechanism of plastic edging (scratching), increases on the wear surface [10].

The data from Tables 1 and 2 testify that annealing at higher temperature (1000 °C) followed by furnace cooling, as compared to annealing at 900 °C, increases hardness and decreases abrasive wear intensity (i.e. increases wear resistance) of the coating both in the initial electropolished state and after friction processing. However, the above-mentioned increase of hardness and, especially, the decrease of wear intensity are more significant for the undeformed coating than for the coating after frictional processing.

The examination by electron scanning microscope and X-ray microanalyzers has shown that, after one-hour annealing at 1000 °C followed by furnace cooling, the structure of the undeformed coating has large elongate $Cr_{23}C_6$ chromium carbides forming a practically closed base framework, Fig. 2b. These carbide particles are much larger than in the initial (prior to annealing) coating (see the bottom part of Fig. 1c). It is by significant structural inhomogeneity that we can explain a very wide dispersion of microhardness values for the undeformed laser coating annealed at 1000 °C, see Table 1. It is the formed carbide framework that causes the least wear intensity (I_h=0.55×10^{-6}, see Table 2) of the undeformed coating annealed at 1000 °C. It was reported in [11] that it is the strengthening phases that make a dominant contribution (as compared with the metal matrix) to the abrasive wear resistance of laser-clad NiCrBSi coatings. Depending on the ratio between the hardness of the strengthening phases (carbides, borides, carboborides) and that of the abrasive particles, different wear mechanisms (microcutting or scratching) are implemented and, consequently, different levels of the wear resistance of coatings are reached [11].

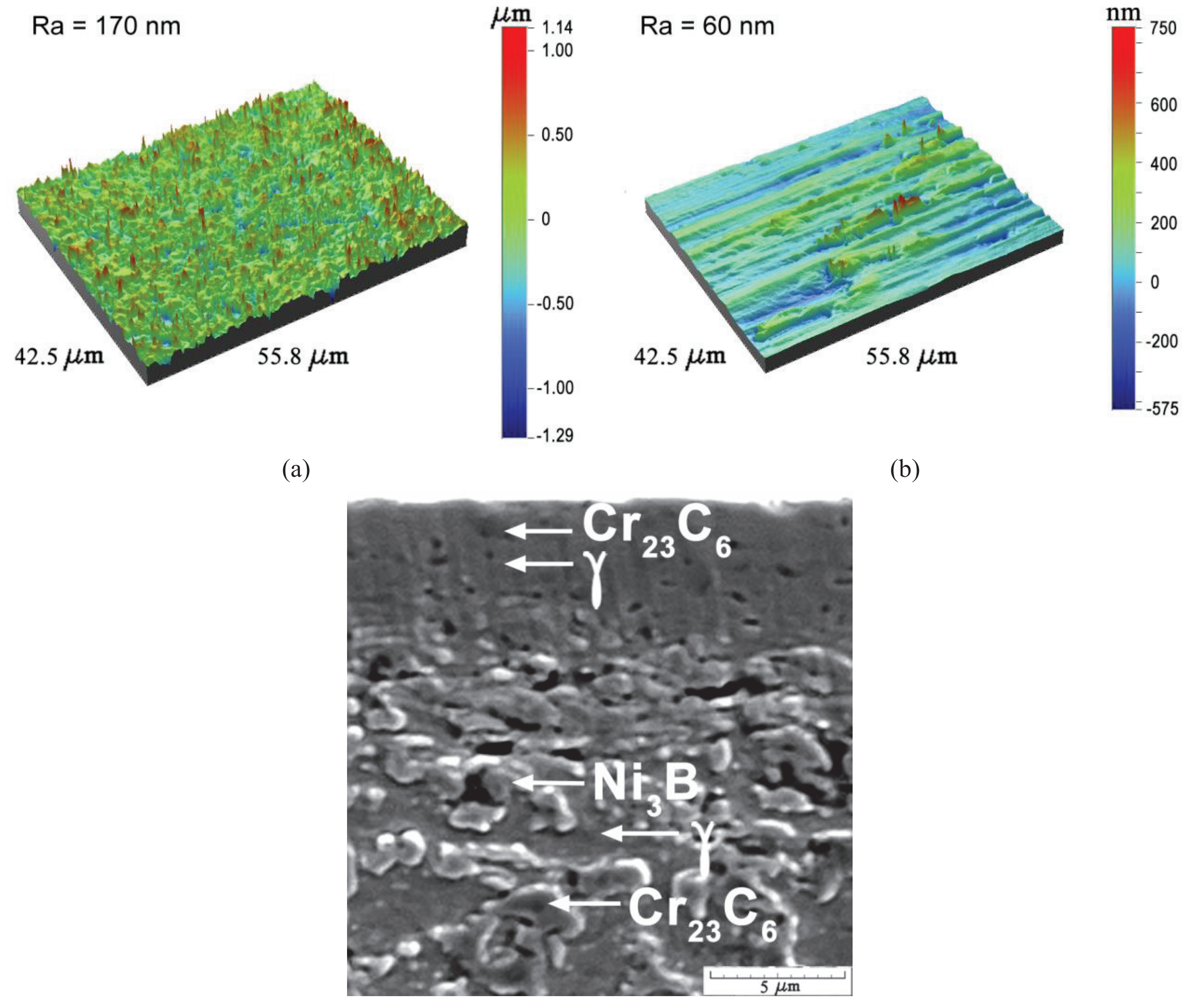


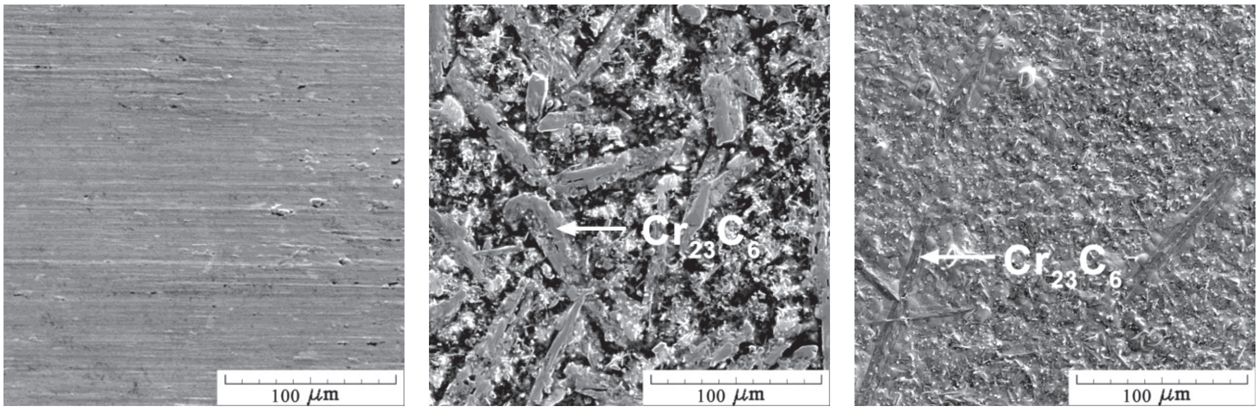
FIGURE 1. Optical profilometry of the surface (a, b) and an electron microscope image of the structure of the transverse section (c) of the coating after electropolishing (a) and frictional treatment (b, c)

TABLE 1. Effect of thermal action on the microhardness (HV 0.025) of the initial electropolished coating and the coating after frictional treatment

Specimen state	Microhardness HV 0.025		
	Without thermal action	**After annealing at 900 ºC**	**After annealing at 1000 ºC**
Electropolishing	570±10	530±35	730±270
Frictional treatment	850±25	640±40	720±155

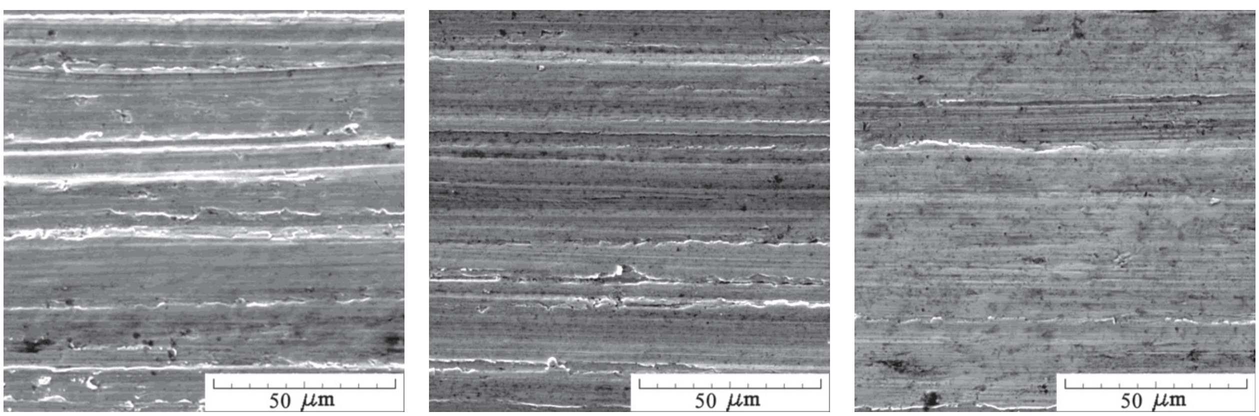
TABLE 2. Effect of thermal action on the abrasive wear intensity of the initial electropolished coating and that after frictional treatment in testing for wear against silicon

Specimen state	Abrasive wear intensity, 10^{-6}		
	Without thermal action	**After annealing at 900 ºC**	**After annealing at 1000 ºC**
Electropolishing	1.05	1.20	0.55
Frictional treatment	0.85	0.95	0.80



(a) (b) (c)

FIGURE 2. Electron microscope images of the coating surface after frictional treatment (a) and combined treatments: electropolishing + annealing at 1000 ºC (b) and frictional treatment + annealing at 1000 ºC (c)



(a) (b) (c)

FIGURE 3. The abrasive wear surfaces of specimens with the PG-SR2 coating in the initial electropolished state and after frictional treatment followed by annealing at 900 ºC (b) and 1000 ºC (c) after testing for wear against silicon

Figure 2c testifies that, as a result of high-temperature (1000 °C) annealing, only separate isolated elongate $Cr_{23}C_6$ carbide particles are formed on the surface of the laser coating strengthened by frictional treatment (see Fig. 2a). These isolated particles do not form a closed framework. This can explain the higher wear intensity (I_h=0.80×10^{-6}, see Table 2) of the laser coating subjected to a combined deformation-heat treatment (frictional treatment + high-temperature annealing) than that of the annealed undeformed coating. However, as compared to laser cladding (I_h=0.80×10^{-6}, see Table 2), frictional treatment followed by annealing at 1000 °C provides lower wear intensity and, consequently, higher abrasive wear resistance. According to Fig. 3c, in testing for wear against a silicon abrasive, the combined deformation-heat treatment restricts the development of microcutting characteristic of the wear of the initial laser coating (see Fig. 3a), and the coating fracture follows predominantly the mechanism of plastic edging (scratching).

CONCLUSION

Frictional treatment by a sliding indenter made of fine-crystalline dense boron nitride not only produces a high-quality surface with low roughness (Ra=60 nm) and increases the hardness and abrasive wear resistance of the PG-SR2 NiCrBSi laser coating, but also stabilizes its properties in a wide range of possible operating temperatures. The 5-7 μm thick surface layer dispersed by frictional treatment, when heated to 900-1000 °C, demonstrates higher levels of hardness and wear resistance in comparison with the undeformed coating.

The annealing of a friction-hardened coating at 1000 °C, followed by furnace cooling (similarly to the same annealing of an undeformed laser coating), results in increased hardness and wear resistance in comparison with softening annealing at 900 °C. However, after frictional treatment, this increase in hardness and wear resistance is less effective than at the high-temperature (1000 °C) annealing of the initial macrocrystalline coating. This is due to the limited precipitation (due to annealing at 1000 °C) of large $Cr_{23}C_6$ carbides, forming a wear-resistant framework in the undeformed coating, on the deformed surface with a dispersed structure.

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